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4.2: High Heat Flux Thermal Management of Microfabricated Upper Millimeter-Wave Vacuum Electronic Devices

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Abstract: *Computations of operating temperatures in microfabricated upper-millimeter-wave sheet beam traveling wave structures are provided. The studies include the effects of different cooling techniques and construction materials. The scaling of output power capability vs. frequency, as constrained by thermal limits, is also presented.*

Keywords: microchannel cooler; DRIE; LIGA.

Introduction

Methods for the high heat flux cooling of microfabricated, upper millimeter-wave vacuum electronic devices based on sheet beams are a topic of considerable interest. A good example for investigation is a sheet beam coupled cavity traveling wave structure [1], which is of interest due to its scalability with power (by making the structure and beam wider) and the broad bandwidth potential. Two complete periods of the bottom half of the structure (each period 0.6 mm long at W-band) are shown in Fig. 1(a). The entire structure is composed of many 10's of periods, but only two are shown for simplicity. The sheet electron beam passes axially through the rectangular central beam tunnel. Note that there is an upper half to the structure (a mirror image with respect to the beam tunnel) that is not shown. The presence of horizontal and vertical coupling slots between the vane-like cavities can significantly interrupt the flow of heat from the beam tunnel area to the surrounding bulk metal.

Analysis Assumptions

An initial thermal analysis at W-band was made by assuming a beam tunnel of 0.6 mm full height and 1.6 mm width, and 3.4 cm total axial circuit length, containing a sheet beam with nominal transverse dimensions of 0.3 mm full height and 1.2 mm width. An operating voltage of 16 kV and total beam current of 680 mA was chosen based on beam-wave interaction optimization studies [1]. The beam power is 10.9 kW continuous wave (CW), so that even a device with an electronic efficiency of 2.5% would make 270 W of CW output power. However, adequate thermal management is critical. Heating in the interaction circuit can come from both RF losses and from beam interception. For initial work, the primary source of heating was assumed to be beam scraping, due to beam halo effects and magnetic focusing problems resulting in a non-laminar

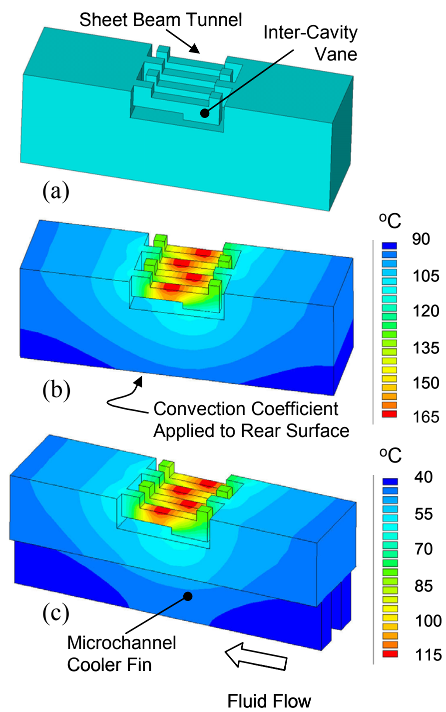

Figure 1. (a) solid model of a portion of the interaction structure; Temperature results from ANSYS models with (b) 2.5 $\mathrm{Wcm^{-2}K^{-1}}$ convection coefficient and (c) built-in microchannel cooler.

scalloping of the beam. A typical beam interception in W-band round beam CC-TWTs is 10%, and if assumed to be relevant for a sheet beam device, 1.09 kW needs to be dissipated in the structure. This translates into a CW power density of 2.0 kW/cm^2 on the surfaces of the inter-cavity vanes that line the beam tunnel. Although high, it is within the range of aggressive liquid cooling technologies such as microchannel coolers. Such coolers at these flux levels and even higher are being investigated for cooling solid state [2] and vacuum electronic devices [3].

Results

An ANSYS model of the structure was created for thermal analysis. Since the most likely ways of making this structure are either electric discharge machining (EDM) or lithography-based electroforming and molding (LIGA), the

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initial thermal analysis assumed a copper structure (thermal conductivity κ of 385 $Wm^{-1}K^{-1}$). Simulations were first run assuming a convective heat transfer coefficient of 1.0 $Wcm^{-2}K^{-1}$ with a 20 °C bulk fluid temperature applied to the external bottom surface of the model, consistent with conventional liquid filled cold-pates or attachment to a large forced-air-cooled heat sink of high quality. The simulation revealed a peak interaction structure temperature of 273 °C, which is much too high for reliable operation (150 °C is a good upper limit). Hence one can rule out the most trivial types of cooling as being ineffective. When the applied convection coefficient on the external bottom surface of the structure was increased to 2.5 $Wcm^{-2}K^{-1}$, the peak temperature dropped to 164 °C, as seen in Fig. 1(b), which is much closer to an acceptable level. This level of convection coefficient can be achieved with moderately aggressive liquid cooling.

Interaction structures made of silicon can also be considered. Silicon, with a thermal conductivity of 150 $Wm^{-1}K^{-1}$, would be the relevant material for devices made by deep reactive ion etching (DRIE) and related processes. The thin metal coatings that are placed on the silicon to support electromagnetic waves have a negligible impact on the thermal conductivity, so the bulk silicon thermal conductivity is appropriate for thermal simulations. If the convection coefficient along the back is maintained at 2.5 $Wcm^{-2}K^{-1}$, then the peak temperature using silicon reaches 275 °C for the 2 kW/cm^2 loading, which is too high. This indicates that the power handing capability of DRIE-fabricated silicon devices will be about ½ of those made from copper if reasonable temperatures and thermal stresses are to be maintained.

Returning to the all-copper structure, it is of interest to examine a specific microchannel cooler design that replaced the bottom 2 mm tall solid Cu base with a 1 mm thick solid base overlying downward protruding microchannel fins. The fins were 600 μm wide by 1.4 mm tall, with the flowing fluid microchannels between the fins also being 600 μm wide by 1.4 mm tall. A convection coefficient of 2.5 $Wcm^{-2}K^{-1}$ was assumed on the channel walls, created by water flowing at 5 m/s velocity through each channel [2]. The ANSYS simulation is shown in Fig. 1(c), and the peak temperature inside the structure is 116 °C. A similar calculation in an all-silicon structure yields a temperature of 224 °C.

The scaling of peak structure temperature with respect to power and operating frequency for the sheet beam coupled cavity TWT structure can be computed by a series of ANSYS runs. Specifically, the structure was scaled down in all dimensions as $1/f$, where f is the frequency. As the frequency increases, the wavelength drops, and to maintain a fixed amount of overmoding in the sheet beam device, the width of the beam and beam tunnel will decrease as $1/f$.

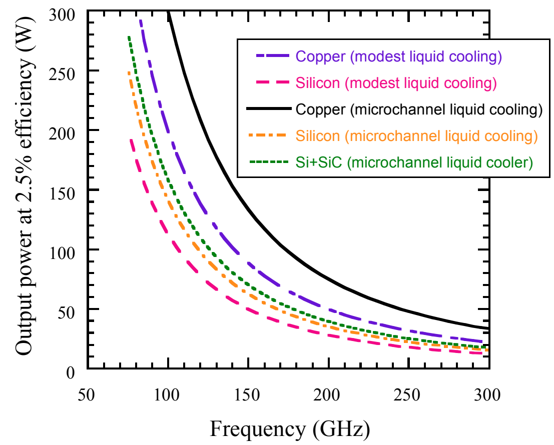

Figure 2. Scaling of limitations on continuous wave output power capability from the sheet beam structure due to thermal management considerations, for 2.5 % electronic efficiency and 10% beam scraping.

Furthermore, the axial period of the coupled cavity structure will decrease by $1/f$ as well. Thus for a given beam power and a fixed percentage of beam interception, the dissipated power density on the inter-cavity walls that line the beam tunnel will increase as f^2, and the temperature will go up dramatically. When combined with a fixed limit on structure temperature (i.e. 150 °C), one can get the scaling of output power capability vs. frequency associated with thermal limits for the structure, for different cooling technologies and materials systems. The results are shown in Fig. 2, which provide a convenient way of viewing the thermal limitations on device power. Further details will be provided in the conference presentation.

Acknowledgements

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